

Water, land, and energy use efficiencies and financial evaluation of air conditioner cooled greenhouses based on field experiments

Ibtihal AL-MANTHRIA¹, Abdulrahim M AL-ISMAILIA^{1*}, Hemesiri KOTAGAMAB², Mumtaz KHANC³, L H Janitha JEEWANTHAD^{4,5}

¹ Department of Soils, Water and Agricultural Engineering, Sultan Qaboos University, Muscat PC123, Oman;

² Department of Natural Resource Economics, Sultan Qaboos University, Muscat PC123, Oman;

³ Department of Plant Science, College of Agricultural and Marine Sciences, Sultan Qaboos University, Muscat PC123, Oman;

⁴ Centre for Future Materials, University of Southern Queensland, Toowoomba QLD 4350, Australia;

⁵ School of Mechanical and Electrical Engineering, University of Southern Queensland, Toowoomba QLD 4350, Australia

Abstract: High temperature and humidity can be controlled in greenhouses by using mechanical refrigeration cooling system such as air conditioner (AC) in warm and humid regions. This study aims to evaluate the techno-financial aspects of the AC-cooled greenhouse as compared to the evaporative cooled (EV-cooled) greenhouse in winter and summer seasons. Two quonset single-span prototype greenhouses were built in the Agriculture Experiment Station of Sultan Qaboos University, Oman, with dimensions of 6.0 m long and 3.0 m wide. The AC-cooled greenhouse was covered by a rockwool insulated polyethylene plastic sheet and light emitting diodes (LED) lights were used as a source of light, while the EV-cooled greenhouse was covered by a transparent polyethylene sheet and sunlight was used as light source. Three cultivars of high-value lettuce were grown for experimentation. To evaluate the technical efficiency of greenhouse performance, we conducted measures on land use efficiency (LUE), water use efficiency (WUE), gross water use efficiency (GWUE) and energy use efficiency (EUE). Financial analysis was conducted to compare the profitability of both greenhouses. The results showed that the LUE in winter were 10.10 and 14.50 kg/m² for the AC- and EV-cooled greenhouses, respectively. However, the values reduced near to 6.80 kg/m² in both greenhouses in summer. The WUE of the AC-cooled greenhouse was higher than that of the EV-cooled greenhouse by 3.8% in winter and 26.8% in summer. The GWUE was used to measure the total yield to the total greenhouse water consumption including irrigation and cooling water; it was higher in the AC-cooled greenhouse than in the EV-cooled greenhouse in both summer and winter seasons by almost 98.0%–99.4%. The EUE in the EV-cooled greenhouse was higher in both seasons. Financial analysis showed that in winter, gross return, net return and benefit-to-cost ratio were better in the EV-cooled greenhouse, while in summer, those were higher in the AC-cooled greenhouse. The values of internal rate of return in the AC- and EV-cooled greenhouses were 63.4% and 129.3%, respectively. In both greenhouses, lettuce investment was highly sensitive to changes in price, yield and energy cost. The financial performance of the AC-cooled greenhouse in summer was better than that of the EV-cooled greenhouse and the pattern was opposite in winter. Finally, more studies on the optimum LED light intensity for any particular crop have to be conducted over different growing seasons in order to enhance the yield quantity and quality of crop.

Keywords: land use efficiency; energy use efficiency; water use efficiency; gross water use efficiency; financial evaluation; air conditioner cooled greenhouse; evaporative cooled greenhouse

*Corresponding author: Abdulrahim M Al-ISMAILIA (E-mail: abdrahim@squ.edu.om)

Received 2020-03-15; revised 2020-05-23; accepted 2020-07-16

© Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Science Press and Springer-Verlag GmbH Germany, part of Springer Nature 2021

1 Introduction

Oman, in general, is classified as an arid and semi-arid country with high temperature and dry climate for most of the year. The range of temperature in Oman may exceed 45°C in summer with an average annual precipitation of 100 mm. High temperature and low annual average precipitation throughout the year indicate that the environment is not suitable for open-field cropping (Jayasuriya et al., 2017). Most vegetables, e.g., tomato, cucumber, pepper, and lettuce, experience a decline in their growth when the temperature exceeds their optimal ranges, i.e., 29°C–30°C (Fath and Abdelrahman, 2005). Therefore, good agricultural management and improved technology can be the key solution to resolve these difficulties.

Controlled Environment Agricultural (CEA) facilities, mainly greenhouses, are used to overcome harsh climatic conditions in water-scarce areas. More specifically, CEA aims to enhance the yield quantity and quality of crop by controlling the environmental factors to be suitable for growing various crops, such as ornamentals, fruits and vegetables (Fogg et al., 1979). It was reported that greenhouses in Oman increased the productivity of land by 12 times compared with open-field farming (Tawfiq, 2009) and promoted the productivity of water by twice (Mazid, 2011). Because of these benefits, the number of CEA facilities in Oman significantly increased in the past 15 a (Mazid, 2011). The most common cultivated crops in greenhouses in Oman are cucumber (90%), followed by tomato (5%–9%) (Mazid, 2011). Kiyumi (2009) considered mono-cropping of cucumber in greenhouses as one cause of some diseases. In Oman, the average seasonal net return (NR) of cucumber and tomato is 742.90 and 368.85 USD per greenhouse (351 m²), respectively (Mazid, 2011).

Fan-pad evaporative cooling system is commonly used in order to cool down the microclimate of greenhouses (Hasan et al., 2009). This cooling method depends on the dryness of the outside air and the solar load (Xu et al., 2015). In summer, the efficiency of fan-pad evaporative cooling system decreases, which makes many greenhouse farmers stop planting during this season (Mazid, 2011). This causes a shortage in the supply of many vegetable crops, and hence price fluctuation occurs. Furthermore, Fadel et al. (2014) reported that fan-pad evaporative cooling systems consumed almost 98.0% of the total electricity consumption and almost 58.0% of the total water consumption in greenhouses under arid climate conditions. Also, Al-Mulla (2006) reported that the amount of water consumed by fan-pad evaporative cooling system alone reached 67.0% of the total greenhouse water consumption.

Mechanical refrigeration cooling systems, such as air conditioner (AC) cooling system, can be an alternative solution to cool greenhouses to obtain optimal ranges of temperature for high-value crops year-round. Although the AC cooling system is less used in commercial greenhouses, it can be an alternative technique for greenhouse cooling (Tabook, 2017). This cooling method has been employed in Taiwan of China, which is a hot and humid region, where growers manage greenhouses to make a good profit (Fang, 1995). There are many advantages of using the AC cooling system, such as meeting the optimal range of temperature for most vegetable crops and some fruits, that is, to provide more choices for greenhouse crops. Also by using the AC cooling system, temperature control will be better, humidity inside the greenhouse could be reduced, year-round cultivation can be achieved, and the evapotranspiration of water can be restored, indicating high water use efficiency (WUE).

The main disadvantages of using the AC cooling system are CO₂ depletion, high energy consumption, and high initial and operational costs (Baird et al., 1993). In warm climates, CO₂ enrichment in greenhouses can be done by simply ventilating (Ioslovich et al., 1995).

Avila et al. (2013) reported that the energy consumption in ventilated greenhouses can be minimized by using fans properly, turning fans on immediately when the temperature exceeds the upper limit and turning fans off immediately when the temperature exceeds the lower limit. This

method of using a fan can also be implemented in AC-cooled greenhouses to decrease the energy consumption.

Another method that can be used to reduce the energy consumption of AC-cooled greenhouses is to reduce the solar heat input by full or partial elimination of solar radiation. However, decreasing the sunlight entering the greenhouse would inevitably lead to a reduction in the photosynthesis process and a subsequent decline in crop growth (Choi et al., 2015). Using light emitting diodes (LED) lights as a source of light can provide the necessary light for the photosynthesis process and emit lower heat than sunlight at the same time. The combination of the red and blue wavelengths of LED lights are the only needed wavelengths for crop cultivation (Choi et al., 2015). Folta and Childers (2008) showed that high strawberry yield can be attained when only the red and blue LED lights were utilized in a growth chamber for 40 d. Therefore, the red and blue LED lights can reduce the energy consumption of AC-cooled greenhouses and provide necessary light for photosynthesis process.

The third method that can be also practiced in AC-cooled greenhouses to reduce the heat load of greenhouses is by diminishing the conductive heat transfer through the covering materials. The materials with lower k and U values have better thermal insulation properties, where k value is the thermal conductivity and U value is the heat transferring rate through a structure (Li et al., 2015). However, all these covering materials have a light transmittance of more than 74.0%, which contradicts with the previous objective of eliminating the solar heat input. To avoid this contradiction, the thermal insulation approach practiced in poultry houses can be used in where rockwool, plastic foam, glass wool mat or mineral filled foam are employed to insulate the structure (Yoshioka and Otani, 2002). Rockwool is a multi-application material that can be used as a thermal insulating roof for industrial, commercial and domestic purposes.

Studying financial feasibility of a new technology is necessary, as financial profitability is a *sine-qua-non* for the private adoption of any technology. In financial feasibility analysis of greenhouse agribusiness, profitability and cash flow budgets are two important measures that have to be conducted. The profitability budget is an analysis of all the return and cost of a particular project during its production cycle. The cash flow budget, on the other hand, is an analysis of all cash in- and out-flows of any particular project for a specific time period.

This study aims to evaluate the techno-financial differences between the AC-cooled greenhouse and the evaporative-cooled (EV-cooled) greenhouse in two different seasons (winter and summer).

2 Materials and methods

This study was conducted in the Agricultural Experiment Station (AES) of Sultan Qaboos University in Oman. Two prototype greenhouses were built with the dimensions of 6.0 m×3.0 m×2.5 m (length×width×height). The study was conducted in two seasons (winter and summer) in order to study the seasonal effect on yield, profitability, water and energy consumption. The control of this experiment is an EV-cooled quonset-type greenhouse, which is commonly used in Oman now (Al-Ismaili et al., 2017). The EV-cooled greenhouse was equipped with a fan-pad evaporative cooling system and two hydroponic irrigation system frames, and was covered by a polyethylene plastic sheet (200 μ m thick) on its surface (Fig. 1a). The dimension of the hydroponic irrigation system frame was 1.20 m height, 1.00 m length, 0.25 m top width and 0.85 m bottom width; it was equally divided into four floors in vertical height, and nutrient membrane technique was adopted in the hydroponic irrigation system. The light source in EV-cooled greenhouse was sunlight. In summer, irrigation water was cooled to a temperature of around 24°C using a water cooling box.

The AC-cooled quonset-type greenhouse (Fig. 1b), which was cooled using a 2.4×10^4 Btu/h window-type air conditioner, was covered with rockwool insulation material (50 mm thick) and double layers of polyethylene plastic sheets. The rockwool insulation material sheet can eliminate solar heat input and conductive heat gain. For enhancing plant growth, CO₂ concentration necessary for photosynthesis process should be more than the atmospheric concentration of 350×10^{-6} – 400×10^{-6} (Vox et al., 2010). But CO₂ concentration in greenhouses was estimated to be less than

the outside concentration due to the absence of ventilation. Hence, early morning ventilation via a small fan to avoid hot air intrusion was conducted to enrich the greenhouses with CO₂ whenever it was found necessary. The CO₂ concentration was measured using a CO₂ probe (SCT-108.002.41 SCT NAVID CO₂ Detector, ScichemTech, USA). Similar to the EV-cooled greenhouse, there are also two hydroponic irrigation system frames in the AC-cooled greenhouse. Ten red and blue LED lights (500 WLED Grow Light, CASTNOO, China) were used as a source of light for the photosynthesis process with four levels of light intensity; they were placed above the hydroponic irrigation system frames, 0.30 m higher than the top of the frames (Fig. 1b).

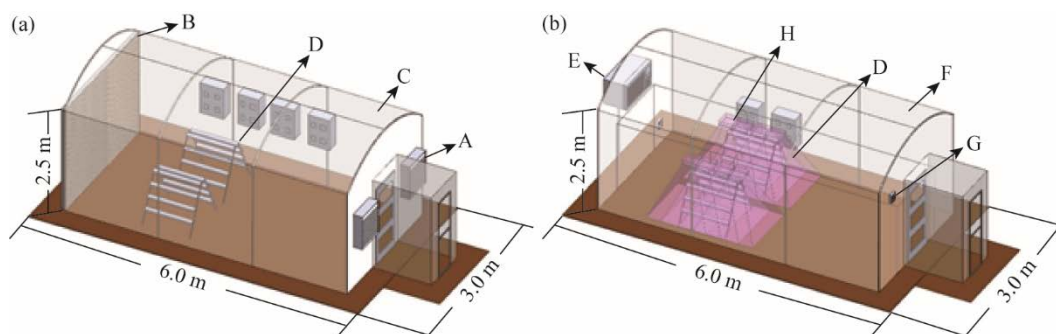


Fig. 1 Illustration of evaporative-cooled (EV-cooled) prototype greenhouse (a) and air conditioner-cooled (AC-cooled) prototype greenhouse (b). The EV-cooled greenhouse is equipped with a fan (A)-pad (B) evaporative cooling system, 200 μ m thick polyethylene plastic sheet (C), and two hydroponic irrigation system frames (D); the AC-cooled greenhouse is equipped with an air conditioner (E), 50 mm thick rockwool insulation material sheet and double layers of polyethylene plastic sheets (F), a small fan (G), two hydroponic irrigation system frames (D), and four different height levels red and blue light emitting diodes (LED) lights (H).

2.1 Technical efficiency

In order to study the technical performance of the AC-cooled greenhouse, we installed Watt-meters to record the electricity consumption of the air conditioner, LED lights and irrigation pumps, and used a water meter to measure the consumption of water for irrigation. Similarly, in the EV-cooled greenhouse, consumption of the electricity of the fans, cooling pump, and irrigation pumps was measured via Watt-meters; the consumption of water for cooling and irrigation was recorded using water meters.

The performance of the greenhouses was evaluated using four efficiency indices, namely, land use efficiency (LUE, kg/m²), water use efficiency (WUE, kg/m³), gross water use efficiency (GWUE, kg/m³) and energy use efficiency (EUE, dimensionless). These indices were calculated at the end of each season using the following equations (Fernández et al., 2007; Al-Busaidi and Al-Mulla, 2014; Fan et al., 2014; Tabook and Al-Ismaili, 2016):

$$LUE=Y/A, \quad (1)$$

where Y represents the yield (kg) and A indicates the cultivated area (m²). The land use efficiency (LUE), also called land productivity, can calculate the weight of the crops production per unit area in any particular period.

$$WUE=Y/ET, \quad (2)$$

where ET is the evapotranspiration loss (m³). In the hydroponic irrigation system, ET is the daily added amount of irrigation water multiplied by the total number of days in the whole season. In general, WUE was used to find the relationship between water consumption and the development of crop growth.

$$GWUE=Y/(IW+CW-RW), \quad (3)$$

where IW is the amount of irrigation water (m³); CW is the amount of water used in the cooling system (m³); and RW is the amount of water recovered from the air conditioner (m³). The GWUE is similar to the WUE, but it compares the total yield to the total greenhouse water consumption including irrigation and cooling water (Tabook and Al-Ismaili, 2016).

$$EUE = \frac{\text{Energy output}}{\text{Energy input}}, \quad (4)$$

where the energy output (MJ/hm²) is the energy equivalents of all outputs, mainly referring the crop yield in this study; and the energy input (MJ/hm²) indicates the summation of energy equivalents of all inputs involved in the production, such as labors, diesel fuel, machinery, manure, chemical fertilizers, electricity, chemical pesticides, seeds and water (Tabook, 2017). Table 1 provides the energy equivalent factors that were used to convert the unit input and output into their corresponding energy values.

Table 1 Energy equivalents of different input and output values used in agricultural production

	Input/output	Unit	Energy equivalent per unit input/output (MJ/hm ²)	Reference
Energy input	Human labour	h	1.96	Singh et al. (2002)
	Rotavator		2.35	Alam et al. (2005)
	Knapsack sprayer		1.40	Gezer et al. (2003)
	Seed	kg	1.00	Taki et al. (2012)
	Diesel-oil	L	56.31	Singh and Kamal (2012)
	Electricity	kW·h	3.60	Ozkan et al. (2011)
	Water for irrigation/cooling	m ³	1.02	Yaldiz et al. (1993)
	Nitrogen	kg	60.60	Singh et al. (2002)
	Phosphorus	kg	11.10	Singh et al. (2002)
	Potassium	kg	6.70	Singh et al. (2002)
	Sulfate	kg	1.12	Mohammadi and Omid (2010)
	Calcium	kg	1.12	Mohammadi and Omid (2010)
	Micro-nutrients	kg	120.00	Banaeian et al. (2011)
	Farm yard manure	kg	0.30	Taki et al. (2012)
Energy output	Pesticides	kg	196.00	Kuswardhani et al. (2013)
	Fungicides	kg	168.00	Kuswardhani et al. (2013)
	Crop yield (lettuce)	kg	1.20	Hatirli et al. (2005)

2.2 Experimental setup

In order to avoid mono-cropping currently practiced in most greenhouses in Oman as well as to get high return from the greenhouse cropping, we planted three cultivars of high-value lettuce in the two greenhouses for experimentation, namely, Butterhead lettuce 'Flandria', Lollo Rose lettuce 'Carmoli' and Frisse lettuce 'Korbi'. After transplanting, the cultivation seasons in both greenhouses lasted for 31 d (19 February 2019–21 March 2019) in winter and 28 d (20 May 2019–16 June 2019) in summer. In a germination room, seeds were grown in sponge cubes (diameter of 0.04 m and height of 0.03 m), which were compatible with the holes of the hydroponic irrigation system. Productivity of crops is adversely affected by temperature when it falls below 10°C–12°C or exceeds 30°C–35°C for several days (Salih and Aydrus, 2015). The lowest daily radiation need by these crops is around 8.5 MJ/(m²·d), which is attained from about 6 h of light per day (Castilla and Baeza, 2013). Regarding relative humidity in greenhouses, it should be between 60% and 80% (Vox et al., 2010). Air temperature, relative humidity and CO₂ concentration were maintained at 24°C, 60%–70% and 350×10⁻⁶–400×10⁻⁶, respectively (Brechtner et al., 2013) during the experiment. Also, pH was adjusted between 5.8 and 6.0 (Brechtner et al., 2013) and the electrical conductivity was 0.15–0.20 S/m (MAF, 2013).

Each floor in both hydroponic irrigation system frames contained 9 plants of each cultivar, i.e., 27 plants growing randomly on each floor, with a spacing of 0.15 m between each two lettuce heads. In the AC-cooled greenhouse, four levels of light intensity were used. The first level was around 0.30 m below the LED lights with light intensity of 890 μmol/(m·s). The second level

was 0.80 m below the LED lights with light intensity of 350–400 $\mu\text{mol}/(\text{m}\cdot\text{s})$, which is the optimum intensity for lettuce (Singh et al., 2015). The third and last levels were respectively 1.30 and 1.80 m below the LED lights with light intensity of less than 150 $\mu\text{mol}/(\text{m}\cdot\text{s})$.

2.3 Financial analysis

For each greenhouse during the two seasons, we calculated the total variable and fixed costs of crop production in order to estimate the seasonal budget. Greenhouses frame and insulation cover sheets, electrical wires, cooling system, irrigation pump, hydroponic irrigation system, LED lights are considered as the fixed cost. While the variable cost includes seedlings, nutrients, electricity and water consumption. Financial productivity (FP, USD/kg), total revenue (TR, USD/hm²), gross return (GR, USD/hm²) and net return (NR, USD/hm²) were calculated using the following equations (Heidari and Omid, 2011; Kuswardhani et al., 2013):

$$\text{FP} = \text{Y}/\text{TC}, \quad (5)$$

$$\text{TR} = \text{Y} \times \text{P}, \quad (6)$$

$$\text{GR} = \text{TR} - \text{VC}, \quad (7)$$

$$\text{NR} = \text{TR} - \text{TC}, \quad (8)$$

where Y is the per unit area yield (kg/hm²); TC represents the total cost of the production (USD/hm²); P indicates the sale price of the product (USD/kg); and VC represents the variable cost of production (USD/hm²).

We used discounted cash flow analysis to estimate the benefit-to-cost ratio and internal rate of return (IRR), and estimated the net annual cash flow through the calculation of the difference between the total cash outflow and inflow of the investment. The net cash outflow involves variable and fixed costs while net cash inflow includes the total revenue from the crop yield (Banik and Ganguly, 2017). A total lifetime of the greenhouse is 20 a, which was used in the calculations. In this study, land cost, tax deductions and depreciation were not considered in the capital and operation costs. In Oman, when water consumption is under 1.89×10^4 L, the water price is around 0.10×10^{-3} USD/L, and when water consumption exceeds 1.89×10^4 L, the water price rises to 0.17×10^{-3} USD/L. Agricultural investments are not taxed in Oman. The interest rate was considered to be 6.0%, which is the average commercial bank interest rate on agricultural loans. Annualization factor (FC) and annualized rate (AN, %) that represents a rate of return for a given period of the year were calculated using the following equations (Ward, 1997):

$$\text{FC} = \text{R} / 1 - (1 + \text{R})^{-\text{life}}, \quad (9)$$

$$\text{AN} = \text{FC} \times \text{Cost}, \quad (10)$$

where R is the interest rate (%); life is the lifetime of the greenhouse (a); and cost is the initial investment cost (USD).

Because Oman is in a policy process of removing energy subsidies, so we conducted sensitivity analysis to evaluate the changes on crop yield, market prices and energy costs on the profitability of greenhouses.

3 Results and discussion

3.1 Winter season analysis

The performances of both greenhouses in winter season are presented in Table 2. The lettuce grows vertically and is calculated per growing floor area (Touliatos et al., 2016). The yield of the EV-cooled greenhouse was higher than that of the AC-cooled greenhouse by 30.0% because in the AC-cooled greenhouse, light intensity was decreasing as the distance of lights to lettuce crops was increasing. As a result, the LUE of the AC-cooled greenhouse (10.10 kg/m²) was lower than that of the EV-cooled greenhouse (14.50 kg/m²). Barbosa et al. (2015) reported that the LUE of greenhouse-lettuce grown in a hydroponic irrigation system in Arizona, USA was 6.80 kg/m². Hence, the LUE of both AC- and EV-cooled greenhouses in our study were higher than the reported value. The WUE was better in the AC-cooled greenhouse (100.32 kg/m³) than in the EV-

cooled greenhouse (96.52 kg/m^3) due to the high consumption of irrigation water in the EV-cooled greenhouse as a result of the air flow. Similarly, the WUE values of both greenhouses were higher than the reported value of 30.00 kg/m^3 for lettuce cultivation in another study (Ünlükara et al., 2008).

Table 2 Performance of the AC-cooled greenhouse and EV-cooled greenhouse in winter

Performance index	AC-cooled greenhouse	EV-cooled greenhouse
Yield per cultivation period (kg)	151.50	217.50
LUE (kg/m^2)	10.10	14.50
WUE (kg/m^3)	100.32	96.52
GWUE (kg/m^3)	100.32	1.98
EUE	0.08	0.10

Note: AC-cooled greenhouse, air conditioner-cooled greenhouse; EV-cooled greenhouse, evaporative-cooled greenhouse; LUE, land use efficiency; WUE, water use efficiency; GWUE, gross water use efficiency; EUE, energy use efficiency. The greenhouse area is 18 m^2 .

We calculated the GWUE to evaluate all water consumption (cooling and irrigation) inside the greenhouses. Since the evaporative cooling system of the EV-cooled greenhouse normally consumed 20.0%–50.0% of the total water consumption of the greenhouse in winter (Tabook and Al-Ismaili, 2016), this large consumption of water made the GWUE reaching 1.98 kg/m^3 in the EV-cooled greenhouse, while it was 100.32 kg/m^3 in the AC-cooled greenhouse due to the absence of water use for cooling.

In terms of energy performance, the total energy output of both greenhouses were lower than the total energy input. The EUE of the EV-cooled greenhouse (0.10) was higher than that of the AC-cooled greenhouse (0.08); both values were less than the reported value of 0.30 in the study of Barbosa et al. (2015). Low energy output (i.e., crop yield) and high energy input explained wherefore the EUE was lower in this study compared with other studies. Tabook (2017) reported that the evaporative cooling system alone consumed around 99.5% of the total electricity consumption in greenhouses. To maximize the EUE, we considered many factors such as using solar energy, improving the yield and minimizing the consumption of energy input (Taki et al., 2012).

In the financial analysis, we assumed six cultivation periods in winter and six cultivation periods in summer since each period had 25–31 d in winter and 20–30 d in summer for greenhouse cultivation. We estimated the average sale price of the three cultivars of high-value lettuce in winter and in summer based on Oman market prices. Annualized investment cost of each item was calculated with respect to an interest rate of 6.0%. The initial capital investments of the AC- and EV-cooled greenhouses in six cultivation periods in winter are shown in Tables 3 and 4, respectively.

The agricultural budgets of both AC- and EV-cooled greenhouses in winter are presented in Table 5. The total investment cost of the AC-cooled greenhouse was higher than that of the EV-cooled greenhouse due to the use of LED lights and rockwool sheet with double layers of polyethylene sheets. Similar to previous study (Mohammadi and Omid, 2010), the fixed costs were lower than the variable costs; in this study the variable costs were higher by around 70.0% and 80.0% than the fixed costs in the AC- and EV-cooled greenhouses, respectively. The total cost of production of the AC-cooled greenhouse in winter was higher than that of the EV-cooled greenhouse by almost 30.0%. The total yield of the EV- and AC-cooled greenhouses (18 m^2) for the six cultivation periods in winter were 1305.00 and 780.00 kg, respectively.

3.2 Summer season analysis

The overall performance of both greenhouses in summer is shown in Table 6. The yield of the two greenhouses was almost equal to $102.00\text{--}103.20 \text{ kg}$ during the six cultivation periods in summer. The LUE of both greenhouses was around 6.80 kg/m^2 , which was the same as the reported value of 6.80 kg/m^2 for greenhouse lettuce cultivation in the hydroponic irrigation

Table 3 Initial capital and annualized investments of an AC-cooled greenhouse (18 m²) with lettuce production in winter

Item	Lifetime (a)	Initial investment cost (USD)	Annualized investment cost (USD)
Hydroponic irrigation system frames	20	1664.00	24.18
PVC accessories	20	36.40	0.52
Aluminum door	10	312.00	7.07
Rockwool sheet with double layers of polyethylene sheets	5	299.00	11.83
Water tank	20	55.90	0.81
Foot valve	3	5.72	0.36
Electrical 1.5 mm wires	10	52.00	1.17
Cooling fans	20	156.00	2.26
AC cooling system	10	390.00	6.80
Irrigation pump	5	23.40	0.93
Binding wires	7	5.20	0.16
Electrical panel enclosure	20	52.00	0.75
LED lights	13	1950.00	36.71
Electrical accessories	5	26.00	1.01
Hydroponic irrigation system	20	1248.00	18.12
Installation	20	1170.00	17.00
Water meter*	5	39.00	1.53
Thermocouple wires*	10	1916.20	43.40
Watt meter*	5	67.60	2.68
PAR meter*	10	1625.00	36.79
RHT sensor*	10	1235.00	27.98
Anemometer*	20	1326.00	19.27
pH/EC meter	10	156.00	3.53
Total		13810.42**	288.94

Note: * indicates that these meters and sensors were used in this experimental work, yet farmers may decide not to use it; ** means that the value is the total cost of initial capital investments of an 18 m² AC-cooled greenhouse with lettuce production. PVC, poly vinyl chloride; LED, light emitting diode; PAR, photosynthetically active radiation; RHT, relative humidity and temperature transmitter; EC, electrical conductivity.

system (Barbosa et al., 2015). Similar to the winter season, the WUE and GWUE were lower in the EV-cooled greenhouse than in the AC-cooled greenhouse due to the high water consumption for irrigation and cooling in the EV-cooled greenhouse. Specifically, the WUE was 41.83 and 30.61 kg/m³ in the AC- and EV-cooled greenhouses, respectively. Due to high water consumption on evaporative cooling system, the GWUE for the AC-cooled greenhouse jumped as high as 47.77 kg/m³ compared with the EV-cooled greenhouse, with the value of 0.29 kg/m³. For the sake of comparison, the WUE of cucumber cultivation was between 47.00 and 64.00 kg/m³ under the summer conditions of Oman (Tabook, 2017). The EUE for both greenhouses was less than 1.00 because of the low yield production (energy output) and high energy consumption in the cooling system (energy input).

Table 7 shows the agricultural budgets of the AC- and EV-cooled greenhouses in summer. The yield reduced in both greenhouses, where the yield in the AC- and EV-cooled greenhouses decreased by almost 15.5% and 50.0%, respectively, as compared to the winter season. Due to the elevated consumption of electricity and water during summer, the variable costs reached 1.07×10^3 and 1.60×10^3 USD in the AC- and EV-cooled greenhouses, respectively. On the other hand, the sale price of lettuce increased during summer, because in hot days, most farmers stop growing inside the EV-cooled greenhouses. Total net return of the AC-cooled greenhouse was higher than that of the EV-cooled greenhouse.

Table 4 Initial capital and annualized investments of an EV-cooled greenhouse with lettuce production in winter

Item	Lifetime (a)	Initial investment cost (USD)	Annualized investment cost (USD)
Hydroponic irrigation system frames	20	1664.00	24.18
PVC accessories	20	36.40	0.52
Aluminum door	10	312.00	7.07
Polyethylene plastic sheet	5	65.00	2.57
Water tank	20	55.90	0.81
Foot valve	3	5.72	0.36
Electrical 1.5 mm wires	10	52.00	1.17
Two cooling fans	20	312.00	4.52
Cooling pads	5	143.00	5.67
Irrigation pump	5	23.40	0.93
Binding wires	7	5.20	0.16
Electrical panel enclose	20	52.00	0.75
Electrical accessories	5	26.00	1.04
Hydroponic irrigation system	20	1248.00	18.12
Installation	20	1170.00	17.00
Water meter	5	39.00	1.53
Thermocouple wires	10	1916.20	43.40
Watt meter	5	67.60	2.68
PAR meter	10	1625.00	36.79
RHT sensor	10	1235.00	27.98
Anemometer	20	1326.00	19.27
pH/EC meter	10	156.00	3.53
Total		11535.42**	220.10

Note: ** means that the value is the total cost of initial capital investments of an 18 m² EV-cooled greenhouse with lettuce production.

Table 5 Agricultural budgets of the AC- and EV-cooled greenhouses in winter

Cost and return components	AC-cooled greenhouse	EV-cooled greenhouse
Total yield in winter (kg)	780.00	1305.00
Price (USD/kg)	4.68	4.68
Gross value of production (USD)	3650.40	6107.40
Variable cost of production (USD)	959.09	1207.44
Fixed cost of production (USD)	266.94	220.06
Total cost of production (USD)	1226.03	1427.50
Per kilogram cost of production (USD/kg)	1.56	1.09
Gross return (USD)	2691.31	4899.96
Net return (USD)	2424.37	4679.89
Benefit-to-cost ratio	2.98	4.28
Financial productivity (kg/USD)	0.63	0.92

Table 6 Performance of the AC- and EV-cooled greenhouses in summer

Performance index	AC-cooled greenhouse	EV-cooled greenhouse
Yield per cultivation period (kg)	102.00	103.20
LUE (kg/m ²)	6.80	6.88
WUE (kg/m ³)	41.83	30.61
GWUE (kg/m ³)	47.77	0.29
EUE	0.03	0.05

Table 7 Agricultural budgets of the AC- and EV-cooled greenhouses in summer

Cost and return components	AC-cooled greenhouse	EV-cooled greenhouse
Total yield in summer (kg)	612.00	619.20
Price (USD/kg)	5.20	5.20
Gross value of production (USD)	3182.40	3219.84
Variable cost of production (USD)	1074.68	1603.68
Fixed cost of production (USD)	266.94	220.06
Total cost of production (USD)	1341.62	1823.74
Per kilogram cost of production (USD/kg)	2.18	2.94
Gross return (USD)	2107.71	1616.16
Net return (USD)	1840.77	1396.10
Benefit-to-cost ratio	2.37	1.77
Financial productivity (kg/USD)	0.46	0.34

Financial productivity of the EV-cooled greenhouse was less than 0.40 but it reached 0.46 in the AC-cooled greenhouse. The benefit-to-cost ratio in the AC-cooled greenhouse was 2.37 which was larger than that of the EV-cooled greenhouse (value of 1.77). These results indicated that summer cultivation of lettuce in both greenhouses was profitable and the cultivation in the AC-cooled greenhouse was more profitable. This could be due to the increased yield and reduced consumption of water in the AC-cooled greenhouse compared with the EV-cooled greenhouse.

3.3 Cash flow model

Two cash flow models were developed (Hood et al., 2005) for the two types of greenhouses, i.e., AC- and EV-cooled greenhouses. The average sale prices of the three cultivars of lettuce (Lollo Rose lettuce 'Carmoli', Butterhead lettuce 'Flandria' and Frisse lettuce 'Korbi') for the two seasons (winter and summer) were obtained from the market. Since high-value lettuce was grown in both greenhouses, the net cash flow was negative in the first year due to the initial cost of investment. From the second year onward, the net cash flow was positive for both greenhouses, varying from 3.04×10^3 to 5.42×10^3 USD/a for the AC-cooled greenhouse and from 8.55×10^2 to 6.52×10^3 USD/a for the EV-cooled greenhouse. This means that the two greenhouses are profitable from the beginning of the second year of investment. It should be noted that in the AC-cooled greenhouse, there is another negative value in the 10th year due to major maintenance work such as LED lights, AC cooler and rockwool sheet. The net present value of the AC-cooled greenhouse was 4.34×10^4 USD with IRR of 63.4%. On the other hand, the IRR of the EV-cooled greenhouse was 129.3% with net present value of 5.94×10^4 USD. The high financial profitability of the EV-cooled greenhouse is due to the higher yield in winter and lower total investment cost compared with the AC-cooled greenhouse. As a result, high-value lettuce cultivation in both greenhouses is very beneficial in Oman, compared with the greenhouse cucumber cultivation that gives IRR of 47.0% (Tabook, 2017).

Sensitivity analysis was conducted on cash flow models for both greenhouses in order to evaluate the effect of potential changes of sale prices, energy cost and yield on the profitability of the enterprise, and the results are shown in Figure 2. Figure 2a and d presents the results of the sensitivity analysis if the annual sale price increased from 0.75 to 3.12 USD/kg. For the AC-cooled greenhouse, the investment became unprofitable (IRR near to 0) at a sale price of 0.75 USD/kg and then turned to be profitable as the sale price increased, almost showing a linear relationship. For the EV-cooled greenhouse, the investment also started unprofitable (IRR=3.6%, less than the interest rate of 6.0%) and then turned to be profitable (exponential growth) as the sale price increased. Generally, it was reported in literature that the profitability of greenhouse cultivation was directly affected by the sale price (Hartz et al., 2007).

Figure 2b and e shows the effects of yield change of the AC- and EV-cooled greenhouses, respectively, on the IRR. As the yield increased, the IRR of both greenhouses increased directly but the increase in the EV-cooled greenhouse was more significant. Figure 2c and f illustrates the

influence of projected subsidy removal of electricity fees on the IRR of the AC- and EV-cooled greenhouses, respectively. In this analysis, 20.0%, 40.0%, 60.0%, 80.0% and 100.0% subsidy removals from the total cost of electricity were evaluated. Results of the sensitivity analysis showed that there was a decrease in the IRR of both greenhouses if the subsidy on electricity fees was removed. Yet, the cultivation of high-value lettuce in both greenhouses would still be profitable even if the subsidy was completely waived. Finally, investment in greenhouses with high-value lettuce cultivation is extremely sensitive to the market price, yield and energy cost.

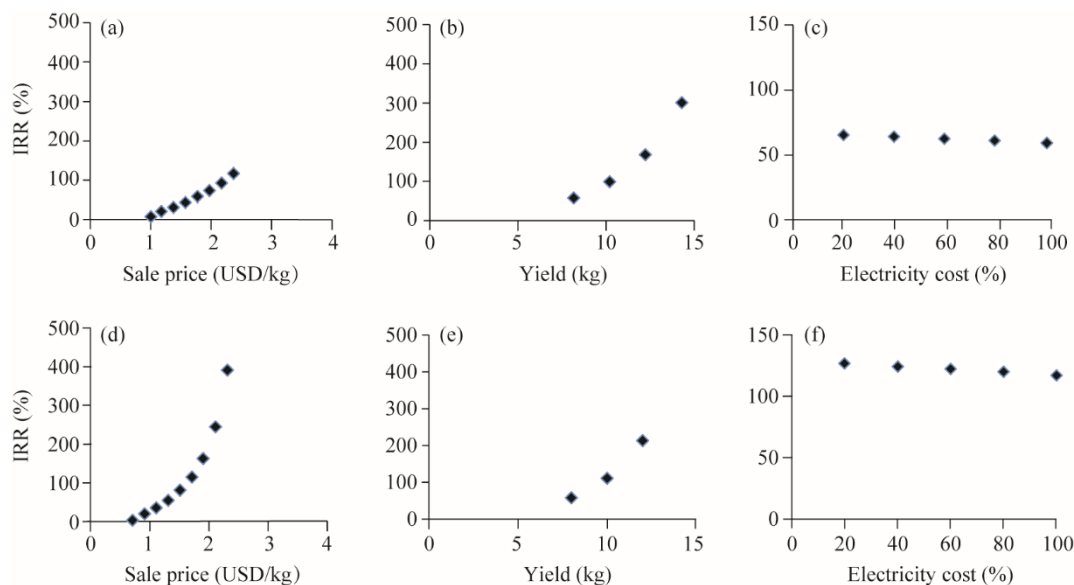


Fig. 2 Relationships of the internal rate of return (IRR) with sale price, yield and electricity cost after subsidy in the AC-cooled greenhouse (a, b and c, respectively) and EV-cooled greenhouse (d, e and f, respectively)

3.4 Benefits of the AC-cooled greenhouse in arid areas

Since agricultural growth and sustainability are adversely affected by high temperature and water scarcity in arid regions (Jayasuriya et al., 2017), the AC-cooled greenhouse system could be an alternative solution to reach optimal temperature range for high-value crops year-round in these areas. By using the AC coolers, temperature can be controlled in winter and summer, and hence year-round cultivation can be achieved and the evapotranspiration of water can be restored, representing high WUE. The AC cooling system in greenhouses is very useful in arid areas suffering from chronic water scarcity as it reduces water consumption (irrigation and cooling) by 98.0%–99.4% compared with the evaporative cooling system. As a result, the variable costs of the AC-cooled greenhouse were less in the EV-cooled greenhouse in both seasons. The fixed costs of the AC-cooled greenhouse can be covered through the cultivation of high-value crops, such as lettuce.

4 Conclusions and recommendations

In conclusion, the LUE of both greenhouses was higher in winter than in summer, because the yield in summer was low. The amount of water use (irrigation and cooling) in the EV-cooled greenhouse was 98.0%–99.4% higher than that in the AC-cooled greenhouse, mainly due to the enormous amount of water that was consumed by the evaporative cooling system. The EUE was higher in the EV-cooled greenhouse in the two seasons. The variable costs in the EV-cooled greenhouse were higher than those in the AC-cooled greenhouse, whereas the fixed costs in the AC-cooled greenhouse were higher. Moreover, the initial investment cost of the AC-cooled greenhouse can be covered through the cultivation of high-value crops such as lettuce. In this study, the investment of greenhouses with high-value lettuce cultivation was extremely

sensitive to the market price, yield and energy cost. The performance of the AC-cooled greenhouse in summer was better than that of the EV-cooled greenhouse, and it was opposite in winter. More research is required to study the AC-cooled greenhouse for a longer period in order to understand the management and maintenance practices required for such a system. Finally, we recommend that renewable energy sources can be utilized to reduce the electricity cost of the AC-cooled greenhouse.

References

- Al-Busaidi H A, Al-Mulla Y A. 2014. Crop water requirement inside conventional versus seawater greenhouses. *Acta Horticulturae*, 1054, doi: 10.17660/ActaHortic.2014.1054.7.
- Al-Ismaili A, Al-Mezeini N, Jayasuriya H. 2017. Controlled environment agriculture in Oman: facts and mechanization potentials. *Ama, Agricultural Mechanization in Asia, Africa & Latin America*, 48(2): 75–81.
- Al-Mulla Y A. 2006. Cooling greenhouses in the Arabian Peninsula. *Acta Horticulturae*, 719: 499–506.
- Alam M S, Alam M R, Islam K K. 2005. Energy flow in agriculture: Bangladesh. *American Journal of Environmental Sciences*, 1(3): 213–220.
- Avila M R, Begovich O, Ruiz-León J. 2013. An optimal and intelligent control strategy to ventilate a greenhouse. Cancun: IEEE Congress on Evolutionary Computation, 779–782.
- Baird C D, Bucklin R A, Watson C A, et al. 1993. Evaporative cooling system for aquacultural production. In: *Fact Sheet EES-100*. Gainesville: University of Florida.
- Banaeian N, Omid M, Ahmadi H. 2011. Energy and economic analysis of greenhouse strawberry production in Tehran Province of Iran. *Energy Conversion and Management*, 52(2): 1020–1025.
- Banik P, Ganguly A. 2017. Performance and economic analysis of a floricultural greenhouse with distributed fan-pad evaporative cooling coupled with solar desiccation. *Solar Energy*, 147: 439–447.
- Barbosa G L, Gadelha F D A, Kublik N, et al. 2015. Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. *International Journal of Environmental Research and Public Health*, 12: 6879–6891.
- Brechner M, Both A J, CEA (Controlled Environment Agriculture) Staff. 2013. *Hydroponic lettuce handbook*. Ithaca: Cornell University.
- Castilla N, Baeza E. 2013. Greenhouse site selection. In: Duffy R. *Good Agricultural Practices for Greenhouse Vegetable Crops Principles for Mediterranean Climate Areas*. Rome: the Food and Agriculture Organization of the United Nations, 21–34.
- Choi H G, Moon B Y, Kang N J. 2015. Effects of LED light on the production of strawberry during cultivation in a plastic greenhouse and in a growth chamber. *Scientia Horticulturae*, 189: 22–31.
- Fadel M A, AlMekhmery M, Mousa M. 2014. Water and energy use efficiencies of organic tomatoes production in a typical greenhouse under UAE weather conditions. *Acta Horticulturae*, 1054: 81–88.
- Fan Y B, Wang C G, Nan Z B. 2014. Comparative evaluation of crop water use efficiency, economic analysis and net household profit simulation in arid Northwest China. *Agricultural Water Management*, 146: 335–345.
- Fang W. 1995. Greenhouse cooling in subtropical regions. *Acta Horticulturae*, 399: 37–48.
- Fath H E S, Abdelrahman K. 2005. Micro-climatic environmental conditions inside a greenhouse with a built-in solar distillation system. *Desalination*, 171(3): 267–287.
- Fernández M D, González A M, Carreño J, et al. 2007. Analysis of on-farm irrigation performance in Mediterranean greenhouses. *Agricultural Water Management*, 89(3): 251–260.
- Fogg L W, Rauhala K R, Satterfield E H, et al. 1979. Controlled environment agriculture facility and method for its operation. America, US4163342. [2020-01-21]. <https://www.freepatentsonline.com/4163342.html>.
- Folta K M, Childers K S. 2008. Light as a growth regulator: controlling plant biology with narrow-bandwidth solid-state lighting systems. *HortScience*, 43(7): 1957–1964.
- Gezer I, Acaroğlu M, Haciseferoğlu H. 2003. Use of energy and labour in apricot agriculture in Turkey. *Biomass and Bioenergy*, 24(3): 215–219.
- Hartz T K, Johnstone P R, Williams E, et al. 2007. Establishing lettuce leaf nutrient optimum ranges through DRIS analysis. *HortScience*, 42(1): 143–146.
- Hasan O, Atilgan A, Buyuktas K, et al. 2009. The efficiency of fan-pad cooling system in greenhouse and building up of internal greenhouse temperature map. *African Journal of Biotechnology*, 8(20): 5436–5444.
- Hatirli S A, Ozkan B, Fert C. 2005. An econometric analysis of energy input–output in Turkish agriculture. *Renewable and*

- Sustainable Energy Reviews, 9(6): 608–623.
- Heidari M D, Omid M. 2011. Energy use patterns and econometric models of major greenhouse vegetable productions in Iran. *Energy*, 36(1): 220–225.
- Hood K, Snyder R, Walden C. 2005. Budget for greenhouse tomatoes. In: Extension Publication 2257. Mississippi Oxford: Mississippi State University.
- Ioslovich I, Seginer I, Gutman P O, et al. 1995. Sub-optimal CO₂ enrichment of greenhouses. *Journal of Agricultural Engineering Research*, 60(2): 117–136.
- Jayasuriya H P W, Al-Ismaili A M, Al-Shukaili T. 2017. Farming systems in Oman and mechanization potentials. *Ama, Agricultural Mechanization in Asia, Africa & Latin America*, 48(2): 66–75.
- Kiyumi K S M. 2009. Greenhouse cucumber production systems in Oman: A study on the effects of cultivation practices on crop diseases and crop yields. PhD Dissertation. Reading: University of Reading.
- Kuswardhani N, Soni P, Shivakoti G P. 2013. Comparative energy input–output and financial analyses of greenhouse and open field vegetables production in West Java, Indonesia. *Energy*, 53(1): 83–92.
- Li F G N, Smith A Z P, Biddulph P, et al. 2015. Solid-wall *U*-values: heat flux measurements compared with standard assumptions. *Building Research & Information*, 43(2): 238–252.
- MAF (Ministry of Agriculture and Fisheries). 2013. Soilless Agriculture in Greenhouses. Kingston: MAF.
- Mazid A. 2011. Assessing returns from investments in two agricultural development projects (protected agriculture and modern irrigation systems) in the Sultanate of Oman. Muscat: International Centre for Agricultural Research in the Dry Areas.
- Mohammadi A, Omid M. 2010. Economical analysis and relation between energy inputs and yield of greenhouse cucumber production in Iran. *Applied Energy*, 87(1): 191–196.
- Ozkan B, Ceylan R F, Kizilay H. 2011. Comparison of energy inputs in glasshouse double crop (fall and summer crops) tomato production. *Renewable Energy*, 36(5): 1639–1644.
- Salih A R S, Aydrous A E. 2015. Compilation and evaluation of wind energy resources in Jebel Awlia area, South Khartoum. *International Journal of Life Science and Engineering*, 1(3): 97–100.
- Singh A K, Kamal S. 2012. Effect of black plastic mulch on soil temperature and tomato yield in mid hills of Garhwal Himalayas. *Journal of Horticulture and Forestry*, 4(4): 78–80.
- Singh D, Basu C, Meinhardt-Wollweber M, et al. 2015. LEDs for energy efficient greenhouse lighting. *Renewable and Sustainable Energy Reviews*, 49: 139–147.
- Singh H, Mishra D, Nahar N M. 2002. Energy use pattern in production agriculture of a typical village in arid zone, India—part I. *Energy Conversion and Management*, 43(16): 2275–2286.
- Tabook S M, Al-Ismaili A M. 2016. Evaluation of greenhouse cropping systems in Oman. *International Journal of Tropical Agriculture*, 34(3): 715–720.
- Tabook S M. 2017. Evaluating the performance of greenhouse cucumber production in Barka. MSc Thesis. Muscat: Sultan Qaboos University.
- Taki M, Ajabshirchi Y, Mahmoudi A. 2012. Application of parametric and non-parametric method to analyzing of energy consumption for cucumber production in Iran. *Modern Applied Science*, 6(1): 75–87.
- Tawfiq A. 2009. The guidelines for techniques of the protected agriculture in Oman. Muscat: The State of Plant Genetic Resources for Food and Agriculture in Oman.
- Touliatos D, Dodd I C, McAinsh M. 2016. Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. *Food and Energy Security*, 5(3): 184–191.
- Ünlükara A, Cemek B, Karaman S, et al. 2008. Response of lettuce (*Lactuca sativa* var. *crispa*) to salinity of irrigation water. *New Zealand Journal of Crop and Horticultural Science*, 36(4): 265–273.
- Vox G, Teitel M, Pardossi A, et al. 2010. Sustainable greenhouse systems. In: Salazar A, Rios I. *Sustainable Agriculture: Technology, Planning and Management*. New York: Nova Science Publishers, Inc., 1–79.
- Ward W A. 1997. *Cost-Benefit Analysis: Techniques and Applications—with Emphasis upon Energy Sector Applications*. Washington D.C.: Economic Development Institute of the World Bank.
- Xu J, Li Y, Wang R Z, et al. 2015. Experimental performance of evaporative cooling pad systems in greenhouses in humid subtropical climates. *Applied Energy*, 138: 291–301.
- Yaldiz O, Ozturk H H, Zeren Y, et al. 1993. Energy usage in production of field crops in Turkey. In: *The Fifth International Congress on Mechanization and Energy in Agriculture*. Izmir, Turkey: 527–536.
- Yoshioka K, Otani M. 2002. Natural feathered fiber insulator. America, US20020034637. [2020-01-15]. <https://www.freepatentsonline.com/y2002/0034637.html>.